An Evaluation of Fabric Insulation and Exposed Thermal Mass to Maximise Adaptive Thermal Comfort

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Abstract
In Northern European climates, passive decarbonisation of building design has predominantly been concerned with limiting fabric U-values. Within a well-insulated fabric however the contribution of internal thermal mass and the dynamics of fabric to air heat exchange become more instrumental in achieving thermal equilibrium. Where high internal gains can also lead to overheating, energy intensive cooling retrofits can become necessary in well-insulated buildings originally designed for natural ventilation. Therefore adequate fabric insulation and internal mass are critical and if more flexible climate controls such as adaptive comfort bands are used, it is be possible to maintain thermal comfort with minimal heating and cooling duties. This work offers a set of indices on the level of insulation and internal mass that can counteract high internal gains (average and maximum aggregated gains of 29.6 W/m^2 and 46.4 W/m^2) in a well-insulated 5-storey office (designed to 2006 UK part L guides) under a mixed mode ventilation regime. Actual summer time surface temperatures collected of the exposed internal concrete in the case study office are on average 3.1°C cooler than concurrent indoor air and are more closely coupled to the running mean of weekly external air temperatures than external daily peaks, allowing the internal exposed concrete to act as a heat sink. Using a calibrated building energy model, the existing static zone target temperatures are replaced with EN 15251 adaptive comfort categories II and III and night purge ventilation to assess the actual building's performance as well as a Passivhaus version under current and future UK Climate Impact Programme (UKCP09) weather data scenarios. Examined in 'freefloat' mode, the actual office building (with overall fabric thermal resistance of 0.61 W/m^2/K and an internal thermal capacity of 167 kJ/k/m^2) achieves adaptive thermal comfort 32% to 52% of occupied hours, whereas a Passivhaus fabric (with overall fabric thermal resistance of 0.27 W/m^2/K and internal thermal capacity of 167 kJ/k/m^2) achieves adaptive comfort 100% of occupied hours across all weather files, with no overheating in either fabric types. Against a static 22°C heating setpoint, adaptive comfort bands II and III can offer heating load reductions of 31% to 69% over current and future weather files.

Keywords: Adaptive comfort; building physics; Passivhaus; Future weather data, homeostatic buildings.

Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BITES	Building Integrated Thermal Storage Systems
BREEAM	Building Research Establishment Environmental Assessment Method
CIBSE	Chartered Institution of Building Services Engineers
DGNB	Deutsche Gesellschaft fuer Nachhaltiges Bauen
HQE	HauteQualité Environnementale

1 Introduction
Buildings account for 32% of the primary energy use worldwide [1], and measures such as passive design techniques, fabric improvement and renewable integration are being deployed (sometimes in isolation from one another) to mediate built-environment carbon emissions. Energy performance building directive EPBD [2] with its European reach decrees minimum building performance requirements. Countries such as UK, France and Germany further promote sustainable design by best practice guidelines such as Building Research Establishment Environmental Assessment Method (BREEAM), HauteQualité Environnementale (HQE), and Deutsche Gesellschaft fuer Nachhaltiges Bauen (DGNB) [3, 4]. The UK dropped its ambition to create zero carbon domestic and commercial buildings by 2016 and 2019, and little clarity exists on how its 2050 carbon targets are to be met. However given that fabric improvements will be a continuing trend, Passivhaus design remains a strong contender for creating zero carbon buildings in colder climates of northern Europe. Extensive field data has demonstrated satisfactory wintertime performance of Passivhaus fabrics, yet summertime overheating risks exist [5] which requires detailed design considerations. A counterbalance to overheating risk in well-insulated buildings is deploying the building structure to act as a thermal energy store (sometimes referred to as thermally activated building systems (TABS)). This concept was extended to introduce the theory of homeostatic buildings [6], where the thermal envelope and internal mass can be optimised to achieve the desired operative temperatures with no or minimal HVAC input (referred to as thermal autonomy). Several other works examine building form design optimisation where window to wall ratio, fabric thermal values, internal mass and HVAC operating temperatures are examined in an integrated manner[6-8] in order to realise zero (or near-zero) energy buildings. Given that office buildings are becoming the dominant workplace in developed countries and are a carbon research priority, this work examines the concept of homeostatic buildings using an actual 5-storey office building (built in 2009 to exceed UK building Regulation Part L 2006 by 30%). In particular focus is maintained on the combined assessment of internal thermal mass and adaptive comfort zone conditioning. Energy analysts predominantly model buildings as empty shells at the design stage which neglects the impact of exposed mass on the natural thermal response of the

building. Thermal mass has a two sided effect on the thermal characteristic of a space, first by providing additional surfaces that will participate in radiative and convective heat transfers, and also by adding mass that is actively impacting the heat extraction characteristics of an internal thermal zone. Thermal mass - be it exposed fabric elements or furniture- will impact the natural thermal response of a building and where high levels of insulation exist, it can moderate internal temperature fluctuations and delay daily peaks beyond office hours when internal gains will also begin to fade. The integrated effect of internal mass (thermal capacitance) and insulation (thermal resistance) could be exploited in the same way as electrical resistors and capacitors where by adjusting the time constant, a low pass filter could be designed to attenuate transients. In a building context, the effect could be thermal autonomy, where the building's natural thermal response can be adjusted to maintain occupied zones within (preferably) climate-linked and dynamic thermal bands (such as those offered by the adaptive comfort theory). This theory is examined within this work where calibrated models of an actual office are used to evaluate the extent that the case study building structure (as thermal energy storage) and fabric insulation can work together to realise zone temperature stability while avoiding summer-time overheating risks. Adaptive comfort bands (as outlined by EN 15251 [9]) are used to replace the static target temperatures in the case study building model (referred to as the base model) as well as a Passivhaus version. Although limited to a case-specific building, standardised thermal resistance and capacitance figures are derived to support similar studies where a holistic approach to passive design techniques are sought to create near-zero or zero carbon office buildings.

2 Background

2.1 Adaptive comfort

Essentially a field-data based theory, this concept defines lower and upper bands within which the neutral temperature of occupant thermal experience lies. It differs from the heat balance model [10] in 3 ways: first recognising the link between local climate and occupant thermal satisfaction, second the variable nature of occupant expectations and finally the occupant's ability to take corrective actions to restore comfort [11, 12]. The first conceptual relationship between perceived neutral temperature (T_n (°C)) and the simultaneous outdoor temperature (T_o (°C)) was offered by M. A. Humphries [13] as follows:

$$T_n = 11.9 + 0.534\, T_o \qquad (R^2 = 0.94) \qquad (1)$$

Where R^2 (the coefficient of determination) illustrates how well formula 1 matches the field study data. Humphries later produced relationships 2 and 4 [14]. Similarly De Dear and Brager [15, 16] used data from 21,000 sites (and 160 buildings) to propose expressions 3 and 5.

In naturally ventilated buildings:

$$T_n = 13.2 + 0.534\, T_o \qquad (R^2 = 0.94) \qquad (2)$$

$$T_n = 13.5 + 0.546\, T_o \qquad (R^2 = 0.91) \qquad (3)$$

In air-conditioned buildings:

$$T_n = 20.1 + 0.0077 T_o^2 \qquad (R^2 = 0.44) \qquad (4)$$

$$T_n = 22.2 + 0.003 T_o^2 \qquad (R^2 = 0.49) \qquad (5)$$

The coefficient of determination for the air conditioned expressions are significantly lower than that of a naturally ventilated building, indicating that adaptive neutral temperature is predicted with greater confidence in a naturally ventilated space. Adaptive comfort is now incorporated by several organisations with an international reach; notably CIBSE Guide A, ASHRAE-55-2013 and ISSO 74 (Dutch code of practice) and EN 15251 [9, 17-19] with a succinct yet precise coverage of these standards available from Olesen and Parsons [20]. Adaptive comfort has been found to offer summertime energy savings [21, 22], and resilience against warmer and more erratic weather patterns anticipated by climatologists in the UK [23] and beyond [24, 25]. It is essential to examine a building's natural thermal response in the context of an acceptable upper and lower temperature band within a free-floating model and therefore adaptive comfort is used in this work to replace current static zone target temperatures in the case study building.

2.2 Passivhaus design

Passivhaus method was primarily developed to offer heating related energy efficiency in moderate and cold climates typified by central and northern Europe. It saw rapid uptakes in Germany, Austria and Switzerland in 90s and 2000s and has also come to influence Scandinavian building standards widely. In Germany and Austria, where the standard was first developed, compliance is satisfied with a maximum final space heating requirement of 15 kWh/m^2 per annum and a maximum overall primary energy use of 120 kWh/m^2 [26]. Passivhaus was reported to outperform similar low carbon developments in the UK dwellings [27] although the imbedded carbon cost [28, 29] as well as solutions for passive cooling [30] highlight the need for careful application of this method. A passivhaus fabric is examined in this work as a mean of stepping up the opaque envelope thermal resistance in the case study building from an average overall of 0.224W/m^{2}K to 0.098W/m^{2}K (an increase of 56%). The glazing thermal resistance is similarly 56% higher in the Passivhaus fabric (0.78W/m^{2}K) compared to the existing building (1.772W/m^{2}K).

2.3 Current and Future weather files

Climate change is not a settled science, yet collective indications point towards continued warming trends with advancing time and carbon emission scenarios. The immediate effect of this in the UK will be an increase in summertime temperatures and more sporadic precipitation [31, 32]. In its latest release United Kingdom Climate Impact Programme (UKCP) provides a set of Cumulative Distribution Function (CDF) and Probability Density Function (PDF) data sets which are recommended by CIBSE for building energy simulation studies. Several research teams have generated future Test Reference Year (TRY) and Design Reference year (DRY) weather files mostly by using Finkelstein- Schafer (FS) and morphing techniques [33-35]. Future weather files used in this paper consist of 85 and 99 percentile climate data derived from spatially downscaled UKCP09 files [33]. This approach uses a baseline period which is the 'observed' trend from 1961 to 2006 (referred to as current weather in this work). Against this observed baseline 'medium risk scenario' 2040 and 2080 weather files are constructed to reflect EU and UK climate mitigation policies [36] (High risk scenarios are mostly used in disaster management studies [37]). Scaling down to 99 percentile years from a collection of 3000 annual forecasts (as provided by UKCIP 09) leads to an inevitable collapse of the distribution of possibilities which is an intrinsic part of the uncertain nature of long term weather predictions. However this method is compliant with CIBSE and EN ISO 15927-4:2005 guidelines [38, 39].

3 Method

3.1 Case study building and energy models

The case-study building is located within a university campus in the North East of England (coordinate: 54˚58´N, 1˚36´W), and has an average electricity to heat demand ratio of 2.5. The building contains 5880m^2 of cellular and open plan office accommodation and 8365m^2 of gross internal space housing a total of about 500 employees (Fig 1).

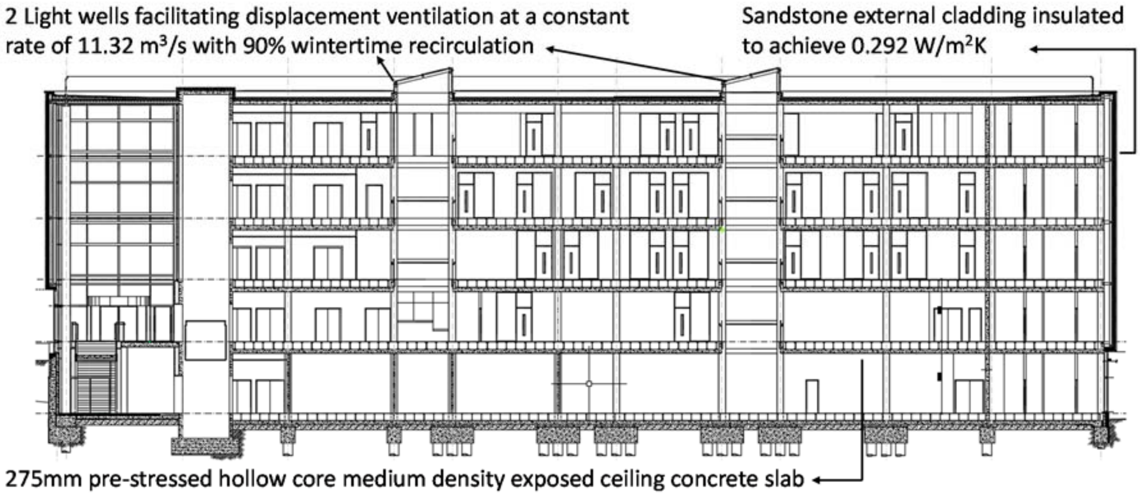

Figure 1: Section drawing of the case study building.

The building was designed to exceed UK's 2006 statutory fabric insulation requirements by 30% and has U-values of 1.772, 0.29, 0.25 and 0.13 W/m^{2}K for glazing, wall, roof and floor elements. It houses an internationally-sourced management and administration team and has heating and cooling set points of 22°C and 24°C. Heating is provided by condensing boilers serving underfloor and perimeter heating as well as acting on incoming air supply. The building is mostly cooled via mixed-mode ventilation with night purge but a 100kW of cooling capacity is provided first by adiabatic evaporative coils acting directly on warmer summertime air intake, followed by direct expansion vapour compression coils in case of excessive heat waves. Given the relatively high internal gains, extensive south-facing fenestration and the well-insulated fabric of the building, the design team sought to eliminate summer-time overheating by the incorporation of thermal mass in the form of 275mm pre-stressed hollow core concrete slabs (medium density and exposed at ceiling level). Due to its high occupant density the building contains a large number of office furnishing that within a well-insulated envelope increases the thermal anchorage effect. In a previous publication [40], an EnergyPlus model of this building was created and calibrated to exceed ASHRAE guide 14 calibration criteria [41]. The EnergyPlus model predicts space air temperature with an accuracy of ±1.5 °C for 99.5% and ±1 °C for 93.2% of annual cycle. Similarly energy prediction accuracy of the base model (i.e. actual building) is within ±5% for Mean Bias Error (MBE) and below 10% for Cumulative Variation of Root Mean Square Error (CV(RMSE)). As such the EnergyPlus model offers very close representation of the operational characteristic of the case study building. Using international Passivhaus association (IPHA) [42] recommended figures, a second model was created by improving the base model fabric to Passivhaus levels while maintaining the exact internal layout and external window to wall ratio (the building's external façades are 53% glazed, with 87% concentrated on a bris-soleil-clad south aspect which is optimised to maximise winter-time solar gain). Basemodel contains actual installed fabric U-values derived from building architects' handbook, while Passivhaus fabric U-values are incremental improvements of the basemodel to satisfy Passivhaus energy use of ≤15 kWh/m^2.yr for heating or cooling.

3.2 Building thermal mass response

As noted already, exposed concrete ceilings were deployed by the design team to form building-integrated thermal energy storage (BITES) and prevent overheating in the case study building. The cooling effect of exposed thermal mass is only robustly reported for active BITES. Reports mostly concern European Alpine climates where cold winters are followed by hot summers requiring architectural solutions that combine high fabric insulation and heavy thermal mass. Thermal storage capacity of 100W/K/m^2 was reported for typical concrete surfaces in a building [43], older literature reported active hollow core concrete slabs to have thermal storage capacities of 10-40 W/m^2 (at ventilation rates of 1.43-2.51 ac/h) [44], and about 50 W/m^2 [45, 46]. To demonstrate the cooling capacity of passive BITES in the case-study building, a TESTO 435 audit unit and FLIR Systems Thermal CAM P660 were deployed to record air and concrete surface temperatures over a 3-month period. The warmest zone (a 5th floor open plant office) at the time of the warmest recorded internal temperatures (i.e. 3-4pm) were chosen to collect average surface temperature of the exposed ceiling concrete. Air temperature was recorded at an optimum recommended distance of 30mm from the ceiling [47], and Lambert radiator method was used to determine the surface emissivity of concrete at 0.91. The audit used a viewing angle of 10°-50° (where 0° is perpendicular).

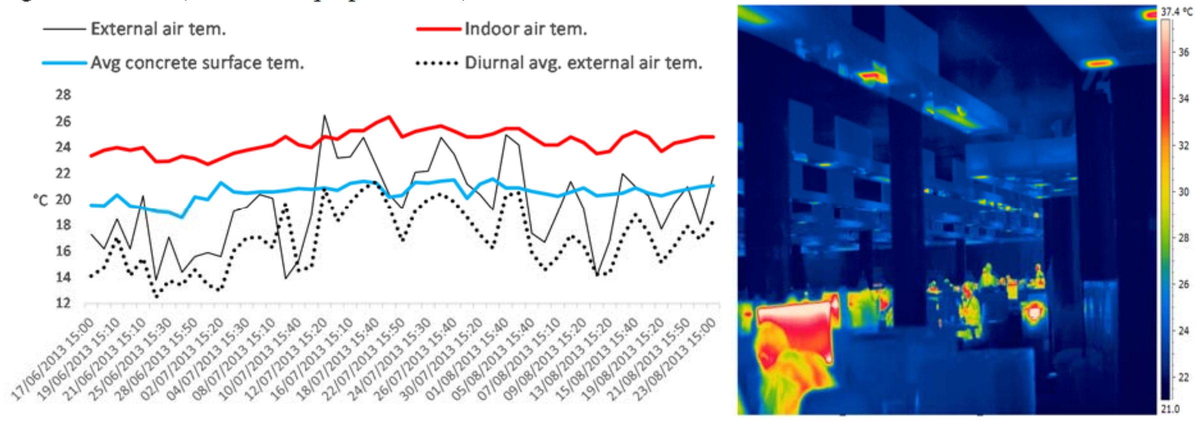

Figure 2: Recorded air and concrete surface temperatures (RHS), thermal audit No 13 (LHS).

The results demonstrated that the exposed concrete surfaces were on average 3.1°C cooler than the instantaneous office air temperature over the 3-month audit (Fig. 2), suggesting a net transfer of heat from the air into the concrete structure during summer days. While the indoor air temperatures across the 49 samples taken had an average of 24.43°C and a maximum of 26.37°C, the average concrete surface temperature remained at 20.54°C with a maximum of 21.6°C. The Pearson correlation value between the concrete surface temperature and external air temperatures at (a) instantaneous hourly (b) running diurnal mean and (c) running weekly mean were 0.577, 0.644 and 0.686 respectively. This illustrates that within a well-insulated building fabric the thermal mass remains more closely coupled to average weekly external air temperatures than instantaneous daytime peaks. This anchorage quality of high exposed internal mass and its ability to help maintaining satisfactory adaptive comfort is examined next while applying the ventilation strategy outlined in Table 1.

Table 1: Ventilation regime (1st April to 1st Nov) as a function of indoor air temperature (T_{in})

Condition	Ventilation rate
Until $T_{in} = 22$°C	Min fresh air [1]
If $T_{in} > 22$°C	1 ac/h
If $T_{in} > 23$°C	2 ac/h
If $T_{in} > 24$°C	3 ac/h
If $T_{in} > 25$°C	4 ac/h
If $T_{in} > 26$°C	5 ac/h
If $T_{in} < T_{outside}$	Min fresh air [1]
Night purge	
If $T_{in} \geq 22$°C at 5pm	Ventilate at 3 ac/h until T_{in}=17°C

Notes:
[1] 10 litre per second per person.
[2] Between 1st November- 1st April the existing building ventilation regime of constant air supply at 11.32 m^3/s using a 90% efficient heat recovery ventilation system prevails.

This core of this ventilation and night purge strategy was adapted from BSRIA BG 2/2009 guide that seeks to cool exposed concrete surfaces prior to each working day and improved via an iterative process to offer the best moderating effect in the case study and Passivhaus building models. Elements that comprise the total thermal capacity of 167 kJ/k/m^2 for both building models are also outlined in table 2.

Table 2: Actual components of thermal capacity within 5 levels of case study office building.

Level	Gross area (m^2)	Partition and fire wall area[1-2] (m^2)	Exposed concrete[1] ceiling (m^2)	Desk stations (No.)	Chairs[4-5] (No.)	Chest[3] of drawers (No.)	Internal structural thermal capacity (kJ/K)	Furniture thermal capacity (kJ/K)
1	2124	526.7	1772.8	90	94	65	326,099.60	11,751.90
2	1820	657.8	1666.2	158	5	118	310.719.9	18,177.30
3	1820	254.8	1666.2	156	50	96	297,467.90	17,551.20
4	1820	219.7	1666.2	180	53	125	297,467.90	20,969.90
5	1590	99	1311.2	24	50	90	231,508.80	7,619.40
					Total (KJ/K)		1,462,269.90	76,069.70

[1] Structural medium weight concrete ceilings and fire walls (Density 1400 kg/m^3 - Heat capacity 0.98 kJ/kg.K)
[2] Light weight Plasterboard (Density 1180 kg/m^3 - Heat capacity 0.8 kJ/kg.K)
[3] Medium Density Fibreboard (Density 720 kg/m^3 - Heat capacity 1.6 kJ/kg.K)
[4] Polyethylene foam (Density 940 kg/m^3 - Heat capacity 1.81 kJ/kg.K)
[5] Polypropylene (Density 900 kg/m^3 - Heat capacity 1.9 kJ/kg.K)

Internal mass represented by actual furniture in the office represent 5% of the total internal mass yet as noted earlier design stage energy simulations do not include this element without which the natural thermal response of the building would be faster.

3.3 Adaptive comfort bands

BS EN 15251:2007 [9] lists four building categories (I-IV); the first three represent high, normal and low occupant expectations (I-III); and the final category (IV) refers to environments where for limited time, temperatures may fall outside those defined by the first 3. Category II is recommended as the norm for normal occupant expectations in a newly built office; therefore performance results are generated for category II and III comfort bands with respective static minimums of 20°C and 19°C as stipulated by table A.2 of EN15251. EN 15251 defines the upper and lower comfort bands (T^{+}, T^{-}) as:

$$T^{+}_{operative} = 0.33\bar{T}_{ao} + 18.8 + Y \quad (6)$$

$$T^{-}_{operative} = 0.33\bar{T}_{ao} + 18.8 - Y \quad (7)$$

Where $T^{+}_{operative}$ (°C) is the upper limit of the acceptable space operative temperature and $T^{-}_{operative}$ (°C) is the corresponding lower limit. $\bar{T}_{ao}$ (°C) is the running mean of the outdoor air temperature over the previous 7 days and Y defines the building category (i.e. $Y_{Category\ II} = 2$, $Y_{Category\ III} = 3$). Therefore a total of 6 pairs of upper and lower comfort bands for building categories II and III were created using 3 sets of weather files (i.e. current, 2040 and 2080). For each building design, the first simulations are performed with and the second without HVAC input to determine the following:

a. Freefloat analysis (ventilation only with no heating or cooling): to determine the basic building envelope response for both base model and Passivhaus versions. In doing so we establish all instances of time (t) when the internal space operative temperature ($T_{operative}$) falls within the adaptive comfort bands ($i.e. T^{-}, T^{+}$). Such instances of time are denoted by the expression $'t_{T_{operative \in (T^{-},T^{+})}}'$, in other words:

$$T_{operative} \in (T^{-}, T^{+}) \quad only\ if \quad T^{-} < T_{operative} < T^{+} \quad (8)$$

b. Energy analysis (HVAC turned on): A second simulation has been performed for each scenario so that the HVAC loads required to bring the space temperature within the adaptive comfort bands can be calculated. The simulation target temperatures are the hourly lower (for heating) or upper (for cooling) adaptive temperatures. These are denoted by expressions $Q_{h(ad)}$ (heating load; kWh) and $Q_{c(ad)}$ (cooling load; kWh).

Zone temperatures and HVAC loads (using both adaptive and static target temperatures) are generated in EnergyPlus software. Current and future weather files were formatted in EnergyPlus weather statistics and conversions program (to create '.stat' and 'EPW' files). In order to avoid instances of heating load in summer, heating season was specified as instances where average 7 day outdoor running mean temperature is below 10°C (i.e. $\bar{T}_{ao}$<10°C) and a 7-day running mean temperature above 15°C ($\bar{T}_{ao}$>15°C) defines the beginning of the cooling season (as defined by EN15251 [48]).

4 Results and discussions

4.1 Overheating and cooling load implications

The average zone upper band target operative temperatures for category II buildings are 23.8°C, 24.4 and 24.9°C in current, 2040 and 2080 weather files. Quite understandably category III band upper limits are 1°C warmer for each weather file. Apart from two single daily instances of cooling requirement in 2040 weather file (which arise from simultaneous high outdoor air temperatures and solar irradiance) no cooling load occurs in any of the scenarios examined.

Table 3: Percentage of annual office time[1] adaptive comfort is met in freefloat mode, i.e. $T_{operative} \in (T^-, T^+)$.

Adaptive comfort category	Weather file	Base model	Passivhaus
Y=2	Current	32	100
	2040	36	100
	2080	43	100
Y=3	Current	41	100
	2040	47	100
	2080	52	100

[1] Office hours: 8am-5pm (weekends and holidays excluded)

As outlined in Table 3, with progressing time and the warming climate, the freefloat condition within the actual building will satisfy adaptive comfort bands II and III progressively more frequently, while the Passivhaus fabric maintains adaptive comfort band with no HVAC input at all times. Fig 3 illustrates that larger number of operative temperatures between 22°C-24°C occurs in the passivhaus model. However instances of summer time temperatures that begin on the upper boundaries of thermal comfort (i.e. 25-27°C) are the same in both models. None of the models exceed the 1% annual time overheating limit of 28°C as defined by CIBSE TM52 [49].

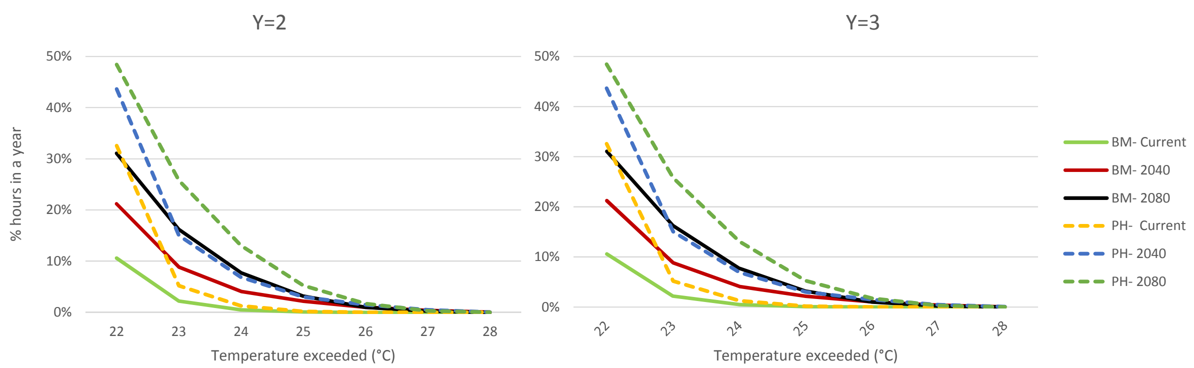

Figure 3: Percentage exceedance chart (annual operative temperatures).

EnergyPlus uses a dynamic Conduction Transfer Function (CTF) to compute surface heat fluxes and it is possible to compute the net heat soaked up by internal thermal mass in both models. Interestingly the simulation results show that while ventilation cooling effectiveness remains similar in both fabrics, thermal mass heat flux in Passivhaus model is nearly 33.7% smaller (Fig 4). For current, 2040 and 2080 weather files, heat absorbed by internal surfaces in the Passivhaus model is 67.1%, 66.1% and 65.7% smaller than that in the Part L base model). This suggests that while for the case study building, the passivhaus fabric meets the adaptive comfort condition most frequently, the thermal mass has a diminished ability to absorb excess summer heat. The reason is that the base model representing the actual building is far more closely coupled with the external climate and therefore experiences much wider internal fluctuations of temperature, whereas a Passivhaus fabric with high internal gains maintains much more constant temperatures, and hence the internal mass of the building stays within a much tighter thermal conditions. Therefore the base model thermal mass experiences much greater thermal fluxes than that of a Passivhaus version.

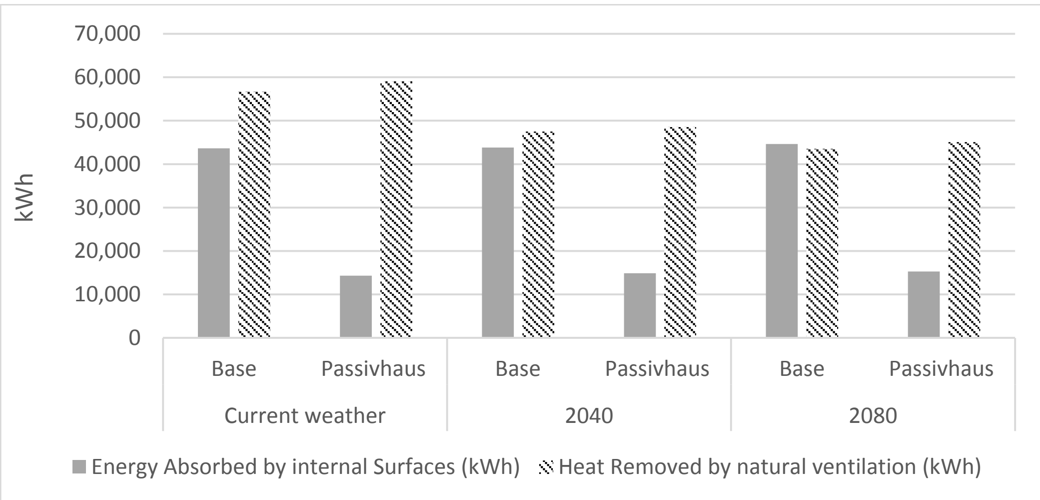

Figure 4: Heat flux instigated by natural ventilation and thermal mass (1 Apr- 1 Nov).

Therefore while improving the building fabric from an overall of 0.61 W/m^2/K to 0.27 W/m^2/K in the case study building lead to internal operative conditions akin to a homeostatic building [6], the summertime cooling effects derived from incorporating 167 kJ/k/m^2 of internal mass begins to diminish at Passivhaus level for Northern European climatic conditions similar to case study location. As a result an optimisation exercise is required to exploit knowledge of building physics and envelope design with site-specific climate knowledge to create well-insulated commercial buildings that require no a little heating and cooling.

4.2 Heating energy implications

Although primarily intended to inform building climate regulation in summer, adaptive comfort offers heating related potential savings when compared to static building setpoints. Heating loads are generated using CIBSE Guide A's static heating target tempeature of 22°C [50] which is currently implemented in the actual building. Using a static heating target temperature of 22°C in the base model, simulation results generates annual heating loads of 332MWh, 195MWh and 146MWh for current, 2040 and 2080 weather files. Against these benchmarks, category II adaptive space conditioning (with a min. temperature of 20°C) produces energy savings of 39%, 37% and 31% in the base model, whereas category III (with a min. temperature of 19°C) returns reductions of 69%, 68% and 58%. Within the Passivhaus model however deploying adaptive comfort removes heating requirements entirely across all weather files. Figure 5 outlines equivalent carbon saving figures based on a gas CO_2 content of 0.18521 kg/kWh [51]. In a heating dominated climate characterised by northern parts of England, it is therefore possible for a Passivhaus fabric in an office with mixed-mode ventilation strategy to maintain adaptive comfort throughout the year in freefloat mode (as outlined in Table 3) where the cumulative effect of high thermal mass, solar control glazing and brise-soleil with natural ventilation work effectively to eliminate summertime overheating too.

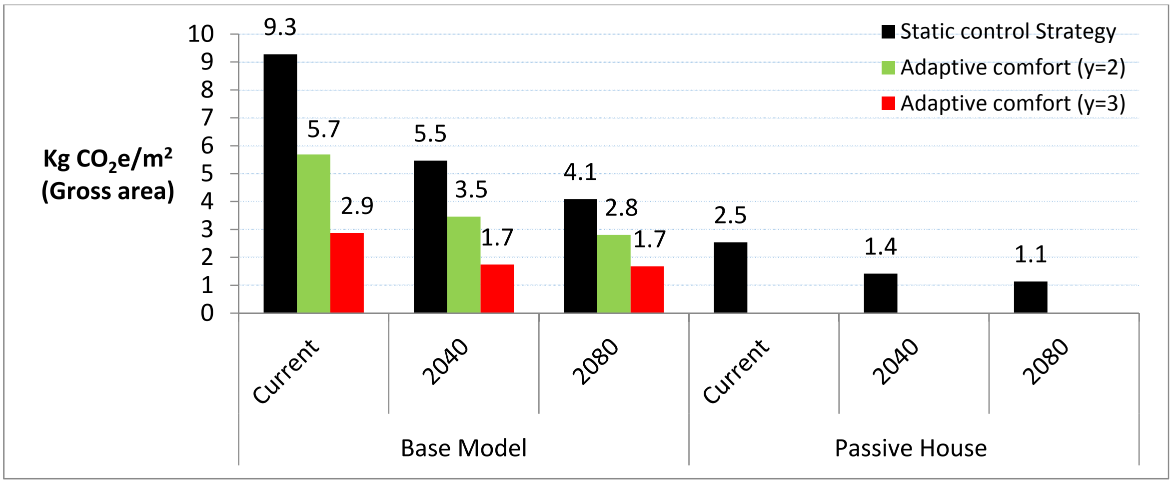

Figure 5: Annual heating related carbon saving resulting from adaptive comfort implementation (Kg CO_{2e}/m^2)

The replacement of existing CIBSE-derived heating set point of 22°C with EN15251:2007 adaptive bands that have minimums of 19°C and 20°C can be viewed as approaching the critical boundary of thermal sensation and this has been highlighted before [52]. However greater occupant tolerance of sustainable buildings can offer a platform to quantify the acceptability of this concept. Similarly geographically diverse field trials found adaptive comfort temperatures as low as 17°C and as high as 30°C to be acceptable in different countries [53]. These occupant climatic adaptabilities could offer further opportunities for the refinement of thermal comfort science particularly as conflicting aspects of the adaptive and heat balance thermal methods remain unresolved [52, 54].

5 Conclusions

The interactions between building thermal resistance and capacitance, the HVAC system and subsequently indoor thermal climate are complex and multi-vectored. Building physics and HVAC characteristics works often falls outside the scope of thermal comfort studies and vice versa. However it is possible to use existing modelling tools to gain insights into how well an existing or proposed HVAC system and climate control regime can work with building active or passive thermal mass, insulation and fenestration to realise a thermostatic building environment with minimum energy input. Within this study minimising HVAC input was examined by simultaneous evaluation of building thermal mass, fabric thermal resistance and EN 15251 adaptive zone controls. Two fabric types, first a UK statutory requirement (which the case-study office is designed to) and an equivalent Passivhaus fabric where examined with a total exposed thermal capacity of 167 kJ/k/m^2 (made of structural elements and furnishing). The existing building has average and maximum internal gains of 29.6W/m^2 and 46.4 W/m^2 across the annual cycle (with a standard deviation of 11.9 W/m^2). Although primarily developed for summertime management under natural and mixed-mode ventilation, adaptive comfort climate control was illustrated to offer winter time heating load reductions of 31% to 69% when compared to static target temperatures of 22°C in winter (by allowing dynamic target temperatures with minimums of

19°C). Daytime and night-purge displacement ventilation did also counteract high internal gains and eliminate overheating risk in the existing and Passivhaus fabrics under current, 2040 and 2080 weather files. The Passivhaus model requires no heating and simulation results showed no summertime overheating under any of the simulated climate files. Natural ventilation is equally successful in removing excess heat in both fabric types, but exposed thermal mass removes nearly three times as much heat in the part L (or existing) fabric type than a Passivhaus version because super-insulation completely isolates and 'de-couples' the passivhaus internal mass from external climatic conditions. Given that exposed mass stays within much tighter temperature bands in a super-insulated building, a state of diminishing returns exists on the viability of incorporating carbon and cost expensive internal mass in super-insulated buildings. Therefore a combination of adequate fabric insulation, thermal mass and adaptive comfort zone conditioning could realise thermal autonomy in free-running buildings under Northern European climatic conditions, if strict and case-specific ventilation and nigh-purge and highly responsive HVAC systems could allow dynamic zone controls with target temperatures that are updated at daily or hourly time steps.

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